Realistic Power-Amplifiers Characterization With Application to Baseband Digital Predistortion for 3G Base Stations

Slim Boumaiza, *Student Member, IEEE,* and Fadhel M. Ghannouchi, *Senior Member, IEEE*

***Abstract*—In this paper, a realistic, accurate, versatile, and thermal-free complex behavior test bed suitable for third-generation power-amplifiers characterization is proposed. Using this approach, a 90-W peak power amplifier based on Motorola-LDMOS class-AB transistors was measured under several signal excitations such as W-CDMA, CDMA2000, and eight-tone signals. The results obtained show noticeable discrepancies compared to those measured using vector network analyzer (HP-8510C) for both AM/AM and AM/PM curves. This test bed was also used for the investigation of the memory effect in RF power amplifiers. In Section II of this paper, the characterization results obtained by the test bed were used to design a digital predistorter for an LDMOS amplifier. A baseband predistortion accurate synthesis algorithm is presented. Indeed, a memoryless baseband digital predistorter lookup table was directly synthesized using the measured AM/AM and AM/PM curves without any need to perform additional analytical derivations and/or numerical optimizations. The predistorter synthesis procedure requires only one iteration, contrary to previous works, which need several iterations to obtain similar performances. This constitutes an important contribution to the digital predistortion technology. The measurement results, under different signal excitations such as CDMA2000, multitones, etc., show great improvement of the out-of-band spectrum regrowth at the high-power-amplifier output.**

***Index Terms*—Distortion, measurements, memoryless pre-distortion, microwave power amplifier, third-generation (3G) applications.**

I. Introduction

HIGH-POWER RF amplifier characterization and modeling has been a subject of study over the last few years. This is mainly driven by the need of a precise behavior model, which represents the nonlinearity of the high power amplifiers (HPAs) and linearizers. This necessity is overwhelming in the new wireless communications applications, where power amplifiers are derived by wide-band digital modulated signals with high peak-to-average power ratio such as third-generation (3G) applications signals.

Mouthrop *et al.* [1] have presented a dynamic measurement method based on two-tone intermodulation calculation to solve the insufficient accuracy in the static method based on continuous wave (CW) signal sweep in the case of varying envelop signals. However, a nonlinearity characterization method [2], exploiting the similarity between a two-tone test and a binary phase-shift keying (BPSK) signal test, indicated dependency of the nonlinearity model on the data rate of the signal applied to the input of the power amplifier. Moreover, it has already been shown [3] that there is a significant difference between pulsed, multitones, and CW measurements when applied to an LDMOS power amplifier.

Therefore, the measured results depend strongly on the input signal. This indicates that it is essential to characterize the power amplifier, in conditions as close to real-life operation as possible, to be able to predict its distortions with accuracy.

The benefits of such precise HPA characterization are especially useful for an accurate HPA's linearizer synthesis. Several linearization techniques such as predistortion, feed-forward, Cartesian feedback, envelope elimination and restoration (EE&R) are used to realize a tradeoff between power efficiency and linearity of the HPA under high varying amplitude input signals. The digital baseband predistortion technique is perceived to be the most suitable and cost-effective linearization technique in the context of 3G wireless signals. This technique takes advantage of the advances of high-speed digital-signal processors and field-programmable gate array (FPGA) technology.

Reference [4] proposed a memoryless baseband mapping predistorter that maps the lookup table (LUT) content in the complex plane. In spite of the low computational load, the iterative algorithm presented for table entry updating has several drawbacks. In fact, the algorithm performances in term of convergence suffer from the dependency on the power output backoff and from the sensitivity to the phase-shifter precision used in the feedback loop. Moreover, the large number of table entries (10^6 complex values) implies a slow convergence, especially in the case of channel switching that imposes a reconvergence. Reference [5] proposed a gain-based predistorter that uses a one-dimensional LUT indexed by the instantaneous input power. In such a way, the number of table entries was greatly reduced and, by consequence, so was the convergence time. The table entry updating was performed using a Secant adaptation method that performs quicker convergence then the linear method used in [4]. However, this algorithm implies a more computational load and it also suffers from the dependency of its convergence speed on the output power and especially near saturation power region. Reference [6] used out-of-band power detection and averaging

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The authors are with the Poly-Grames Research Center, Electrical Engineering Department, École Polytechnique de Montréal, Montréal, QC, Canada H3V-1A2 (e-mail: boumas@grmes.polymtl.ca; fadhel@grmes.polymtl.ca).

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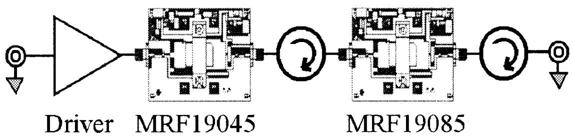

Fig. 1. 90-W peak power-amplifier line up.

at the HPA output for adaptive adjustment of the coefficients of the two polynomial functions that interpolate the HPA inverse nonlinearity. The adaptive algorithm used in this technique belongs to the direct search algorithms family that suffers from the low speed of convergence.

In conclusion, all previously sited studies use iterative methods for the predistorter adjustment to take in to account the HPA behavior variations. Even though they use different adaptation techniques, they all suffer from their slow convergence, in the context of 3G signals, since the table entries are adjusted one by one iteratively. Moreover, adaptive techniques using third- or fifth-order polynomial functions for the predistorter implementation are insufficient to accurately model the optimal predistorter function, especially in the case of class-AB amplifiers. These previous methods are not suitable for 3G wide-band signals since they will require very high-speed signal processors and may be difficult to realize in practice. Contrary to these approaches, [7] presented a first attempt to design an adaptive baseband/RF predistorter using AM/AM and AM/PM based on instantaneous HPA characterization. In this paper, a comprehensive and complete measurement-based predistortion synthesis technique is performed in one iteration.

This paper presents an automated, precise, and versatile test bed to characterize HPAs feed with a wide-band signal such as WCDMA and CDMA2000 (SR3). The characterization results obtained are directly used to synthesize a digital baseband predistorter in just one iteration without any need to perform any additional calculations for the HPA modeling and/or predistortion synthesis purposes.

This paper is organized as follows. In Section II, we first present the line up of the HPA used for measurements, along with details of this new proposed test bed. Following this, we analyze the results obtained from this test bed and compare them with those measured using a vector network analyzer (VNA) and a peak power analyzer (PPA). We will also present some measurements highlighting the memory-effect phenomenon in the behavior of the amplifier. In Section III, we describe the digital predistorter synthesis and implementation procedures based on AM/AM and AM/PM dynamic characterization of the HPA. The linearized HPA shows relatively very good improvement of the spectrum regrowth at its output.

II. Power-Amplifier Characterization

A. Test Circuit

A three-stage HPA for a wireless communication band of 1930–1990 MHz was designed and built for the purpose of this study, as shown in Fig. 1. Its final stage uses a 20-W average class-AB power amplifier (Motorola LDMOS MRF19085). The second stage is built on the LDMOS MRF19045 amplifier. The first stage is used as a gain block to drive the two other stages. The overall small-signal gain of this lineup is 58 dB. The HPA peak output power at 1-dB gain compression is approximately 49 dBm.

B. Test Setup

Fig. 2 shows the proposed test-bed configuration. It includes the vector signal generator (SMIQ) in combination with in-phase/quadrature (I/Q) modulation generator (AMIQ). Software used to generate the test signal is WinIQSIM (version 3.6) from Rohde and Schwarz and Advanced Design System from Agilent Technologies. In fact, a CDMA-2000-SR3 (direct spread) signal is first synthesized with the ADS CDMA2K library. The synthesized signal, with a crest factor equal to 9.69 dB, is then uploaded to the AMIQ. The up-converted output signal of the SMIQ is then fed to the HPA for characterization purposes. The SMIQ-B47 option that consists of baseband filters is used for an enhancement of the generated signals adjacent-channel power ratio (ACPR). Fig. 3 shows the double-channel down-converter used to translate input and output signals to an IF. The down-converter has to be designed carefully in order to get the quasi-same complex mixing function in the two paths. Moreover, an external IF calibration may be applied to compensate for the frequency-translating devices unbalance effects between the two paths. The IF1 and IF2 outputs of the down-converter feed the two baseband channels of the vector signal analyzer (VSA) 89610B. A 20-MHz IF frequency is chosen in order to exploit the full 40-MHz bandwidth of the VSA. A laptop in this test bed is used to run the vector signal analysis software for the acquisition of the two-channel baseband waveform signals. It also serves to capture the complex modulated signals at the input and output of the power amplifier. The delay calibration function of the VSA is exploited to compensate for the time lag between the two channels caused by the group delay of the device-under-test.

The characterization carrier frequency band of the test bed covers 200 MHz up to 3 GHz. This upper frequency can be further extended to millimeter frequency by just changing the mixer used for down-conversion purposes.

C. Measurement Results

Using the proposed test bed, several measurements have been made on the 90-W peak amplifier (20 W average). In the first step, we compared the measurements obtained using the proposed test bed with those obtained utilizing a PPA and a VNA. The signal used to derive the power amplifier for the experiment with the proposed test bed and the PPA is a forward link multicarrier (3×) CDMA 2000 signal with a 3.6864 Mc/s. The peak-to-average power ratio of this signal, at 0.001%, is 12.75 dB. Fig. 4 shows a good agreement between the test bed and PPA results in terms of the gain magnitude compression. Contrary to this, Figs. 4 and 5 demonstrate a significant difference of the gain magnitude and phase compression with those obtained with a VNA power-sweep CW measurements. The similarity of the magnitude gain compression measurement from the PPA and proposed test bed is due to the fact that the two setups perform an instantaneous characterization of the HPA. However, the phase information is absent in the PPA. The discrepancies between VNA results and those obtained using

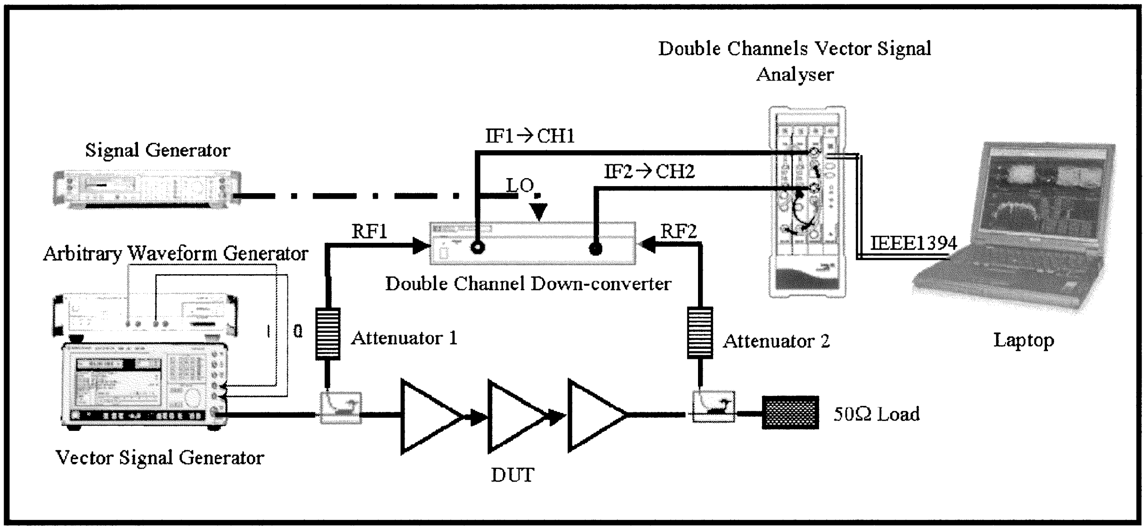

Fig. 2. Proposed test-bed block diagram.

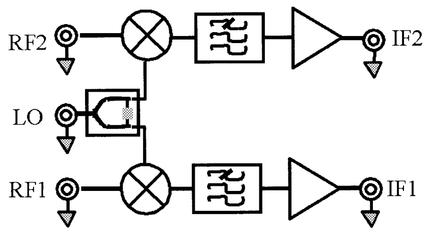

Fig. 3. Double-channel down-converter block diagram.

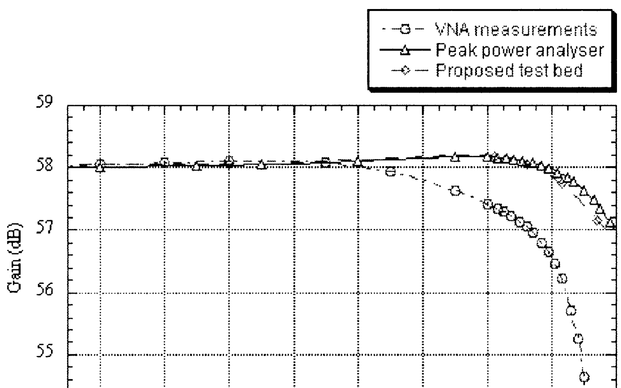

Fig. 4. Gain versus input power measurements with a VNA with a CW signal, PPA, and the proposed test bed with a CDMA 2000 signal.

the two previous methods are due to the long time sweep of the VNA. In addition to this, the amplifier is not supposed to support a high output power in the high nonlinearity region for a long time interval. This explains the high gain compression compared to the other results. The measured peak $P_{1\text{ dB}}$ of the test circuit obtained using the proposed test bed and the PPA is approximately 49 dBm. However, the value obtained by the VNA is approximately 46.5 dBm. This shows the inaccuracy of the traditional VNA gain compression measurements compared to instantaneous characterization results.

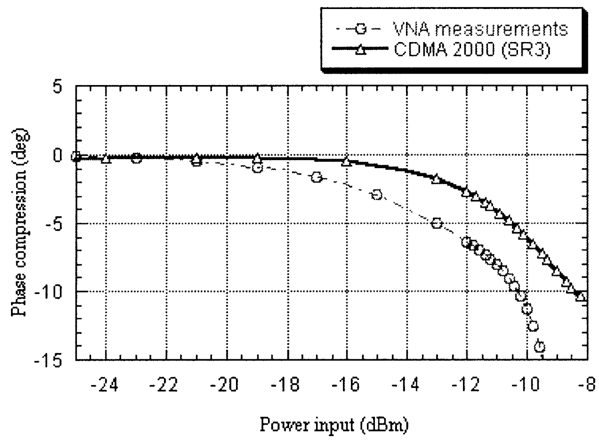

Fig. 5. Gain compression versus input power measurements using a VNA with a CW signal and the proposed test bed with CDMA 2000 signal.

The proposed test bed was also used to measure the complex gain compression of the PA for different signal excitations. In addition to the CDMA 2000 signal used in the previous experiments, we derived the test circuit with a forward WCDMA signal of 3.84 Mc/s having a crest factor equal to 13.35 dB, as well as with an eight-tone signal with 500-kHz spacing. Figs. 6 and 7 show, respectively, the magnitude and phase compression for the above three signals. We can observe the good agreement of the complex gain compression for the different excitations. The similarity of the power-amplifier behavior, when excited by three signals, can be explained by their high common crest factor. This crest factor implies a great variation of the signal envelope and, thus, a comparable operation condition.

This test has been used to study the memory effect in power-amplifier behavior as well. Usually, a two-tone signal is used to characterize this phenomenon [8] and [9]. However, this signal cannot derive the power amplifier in the high nonlinearity region because of its low peak-to-average power ratio. To visualize and measure the memory effects due to the HPA, a phase-aligned eight-tone signal, having a crest factor of approximately 9 dB, is used. Real-time capture of

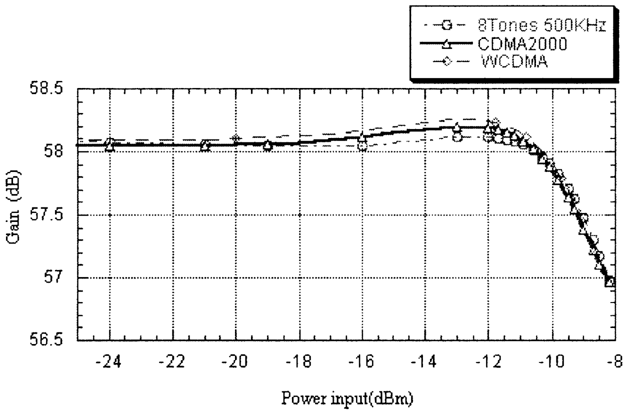

Fig. 6. Gain versus input power measurements for an eight-tone signal with 500-kHz spacing, CDMA2000 (SR3), and WCDMA.

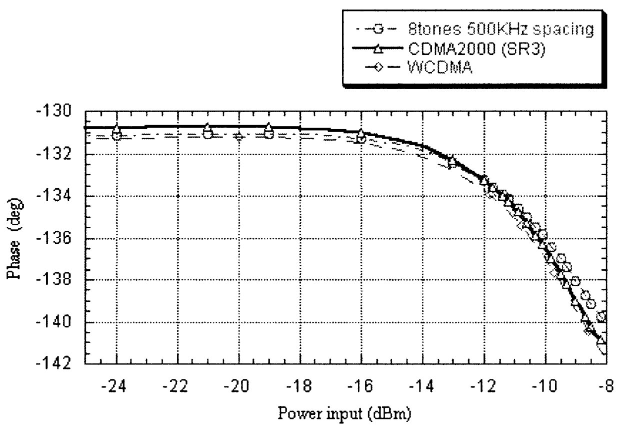

Fig. 7. Phase versus input power measurements for an eight-tone signal with 500-kHz spacing, CDMA2000 (SR3), and WCDMA.

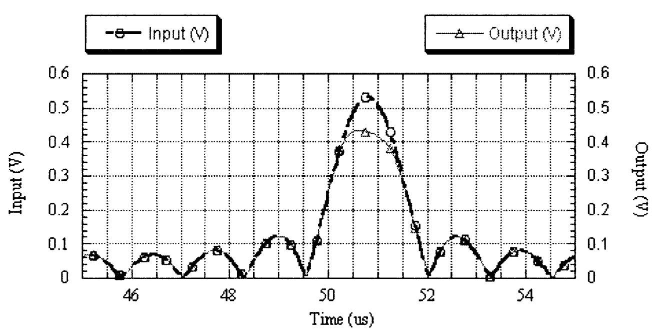

Fig. 8. Input and output waveforms for an eight-tone signal with 100-kHz spacing.

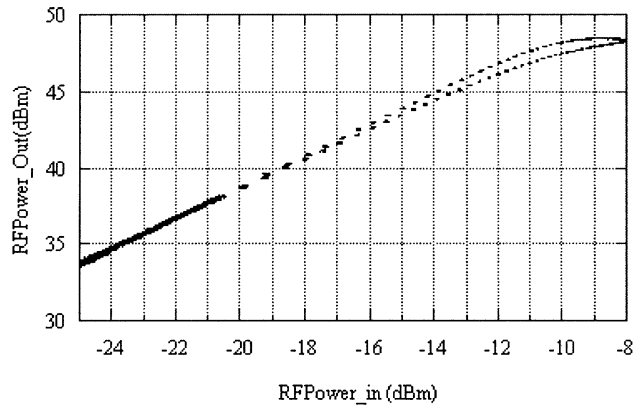

Fig. 9. Output power versus input power for an eight-tone signal with 100-kHz spacing.

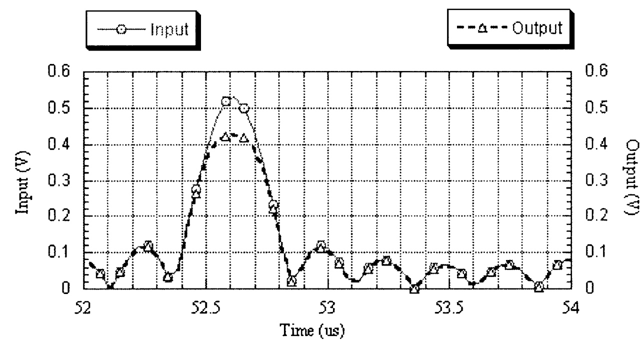

Fig. 10. Input and output waveforms for an eight-tone signal with 500-kHz spacing.

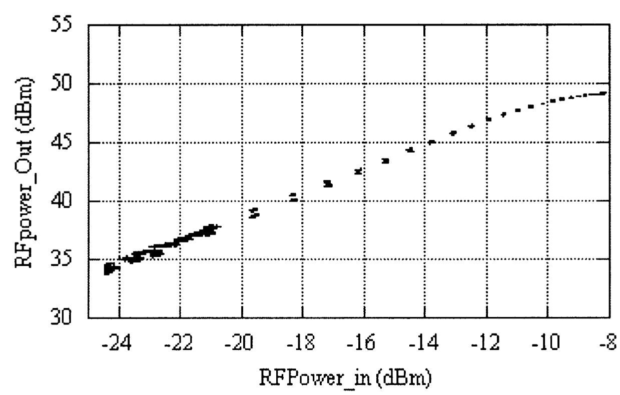

Fig. 11. Output power versus input power for an eight-tone signal with 500-kHz spacing.

the waveforms at the input and output of the power HPA is carried on. Several experiments took place at different tone spacings of the driving signal. Figs. 8 and 9 show the input and output waveforms in the time domain of the power amplifier derived with an eight-tone signal with 100-kHz spacing and the output power versus input power for the same excitation signal, respectively. At this frequency spacing, a hysteresis is clearly observed. However, this phenomenon is not observed for an eight-tone signal with a 500-kHz spacing, as shown in Figs. 10 and 11. Other measurements made for other frequency spacing reveal the presence of this phenomenon for a spacing frequency between 20–130 kHz. This can be explained by a thermal memory effect, which is mostly present at low-frequency spacing [10].

III. Memoryless Digital Baseband Predistortion

Given the obtained HPA characterization AM/AM and AM/PM results, the predistorter function is then deduced in just one step. Thus, the accuracy of the predistortion synthesis technique is directly linked to the accuracy of the instantaneous measured AM/AM and AM/PM characteristics. Fig. 12 illustrates the bloc diagram of the gain-based predistorter employed. Fig. 13 shows the predistorter AM/AM and AM/PM curves implemented with the LUT indexed with the squared magnitude of

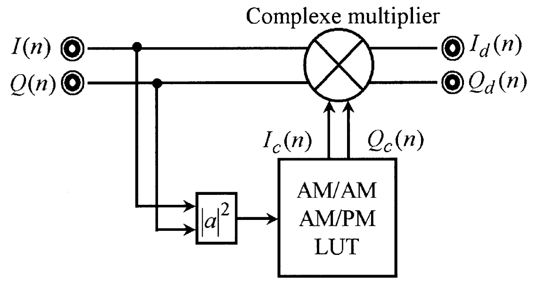

Fig. 12. Memoryless digital baseband predistorter.

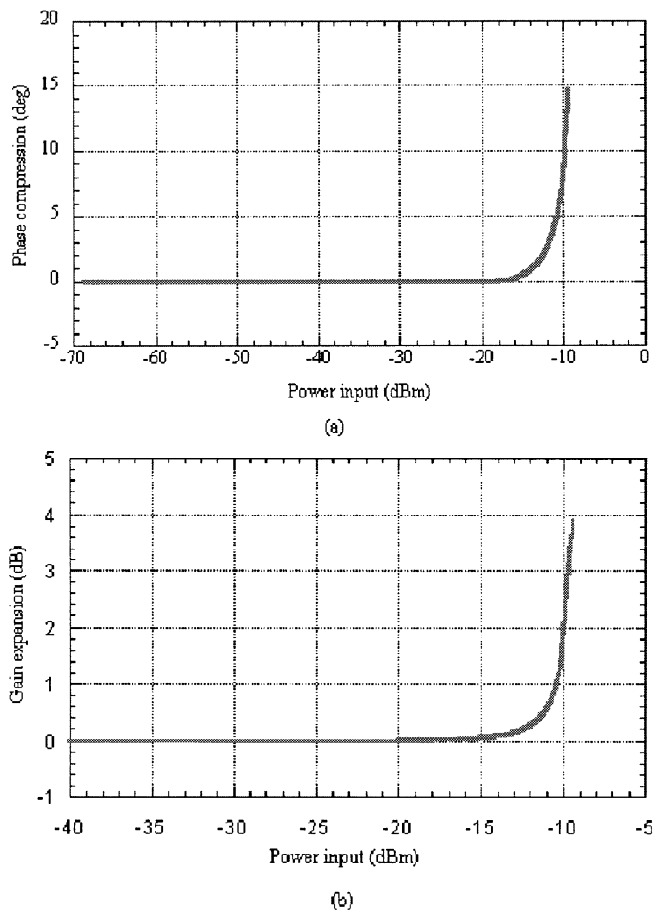

Fig. 13. Predistorter AM/AM and AM/PM curves.

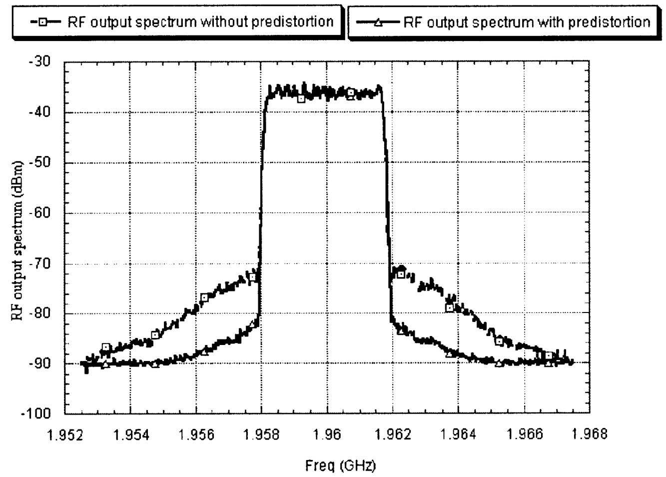

Fig. 14. HPA output spectrum with and without predistortion ($\mathrm{PEP} = 49.3$ dBm) for a CDMA2000 input signal.

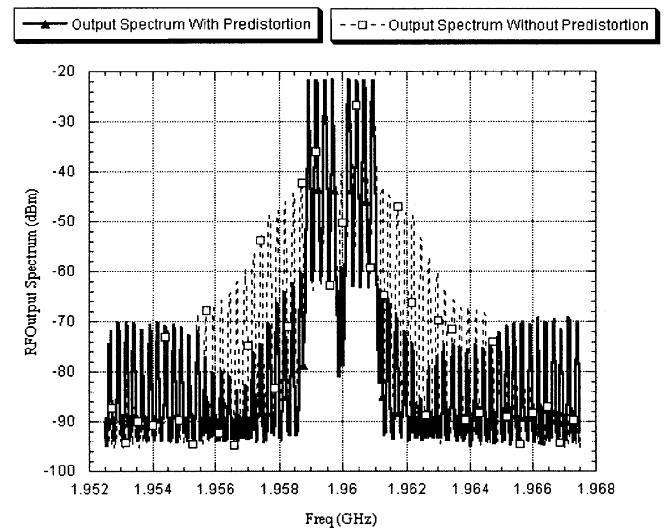

Fig. 15. HPA output spectrum with and without predistortion ($\mathrm{PEP} = 49.3$ dBm) for an eight-tone input signal.

the input signal. The validation of the synthesized predistorter LUT is carried on using Agilent ADS software RF/digital signal processing (DSP) simulation capabilities. ADS signal-generation libraries were used for signals syntheses. A single-carrier forward-link SR3 direct-spread RC6 radio configuration CDMA 2000 signal is used for the first experiment here. Its crest factor equal is equal to 9.69 dB. The synthesized predistorter LUT was used to generate a predistorted version of the synthesized signal. The predistortion function has implied an increasing crest factor. Thus, the predistorted signal, with a crest factor equal to 13.5 dB, is then uploaded to the AMIQ and the SMIQ to feed the power amplifier. Fig. 14 shows an HPA output signal spectrum with and without predistortion with an output peak envelope power equal to 49.3 dBm. The latter indicates significant reduction in the out-of-band emission at the linearized HPA output. The same experiments are repeated under a phase-aligned eight-tone signal with 500-kHz spacing (9-dB crest factor). Fig. 15 shows the measured HPA output signals spectrum with and without predistortion with a peak envelope power equal to 49.3 dBm. As we can observe in Fig. 15, the predistorter out-of-band improvement, in this case, is much more important. Theoretically, the HPA linearized output spectrum should be free from out-of-band emission as its original input signal spectrum. The limit of the quality of the linearization observed in the two experiments is due to three main factors. The first is the nonnegligible memory effect in the case of an HPA. The second is the quantization error. The last is the low-power-range distortion (small-signal gain variation) for class-AB operation. All these factors are not well taken into account in the predistorter implementation. The RF vector modulator impairments in the SMIQ vector signal generator used for signals generation may contribute to the limit of the linearization quality by introducing some distortion not taken in to account.

IV. Conclusion

This paper has proposed an accurate complex-behavior capture test bed suitable for the characterization of power devices under realistic test conditions. The test bed was used to characterize a 90-W peak LDMOS amplifier under different modulated bandlimited signals. This test bed allows the thermal-free characterization of the amplifier over its whole power range. In addition, memory effects can be investigated using the developed test bed. In Section II, the characterization results have been used as an input to the one-iteration step predistorter synthesis procedure proposed in this paper. A memoryless baseband digital predistorter LUT was directly synthesized using the AM/AM and AM/PM measured curves. The predistorter synthesis procedure, in this study, was done in only one iteration that constitutes an important enhancement over previous published techniques that requires close-loop operation and multiiteration convergence synthesis procedures. The measured results, under different signal excitations (CDMA2000, multitones), show a great improvement of the out-of-band spectrum regrowth at the HPA output.

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References

[1] A. A. Moulthrop, C. J. Clark, C. P. Silva, and M. S. Muha, "A dynamic AM/AM and AM/PM measurement technique," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, Denver, CO, June 8–13, 1997, pp. 1455–1458.

[2] M. S. Heutmaker, J. R. Welch, and E. Wu, "Using digital modulation to measure and model RF amplifier distortion," *Appl. Microwave & Wireless*, pp. 34–39, Mar.–Apr. 1997.

[3] O. Anderson, P. Malmlöf, and D. Wisell, "Nonlinear characterization of multiple carrier power amplifiers," in *56th ARFTG Conf. Dig.*, Boulder, CO, Nov.–Dec. 30–1, 2000, pp. 111–118.

[4] Y. Nagata, "Linear amplification technique for digital mobile communications," in *IEEE Veh. Technol. Conf.*, vol. 1, May 3–4, 1989, pp. 159–164.

[5] J. Cavers, "Amplifier linearization using a digital predistorter with fast adaptation and low memory requirements," *IEEE Trans. Veh. Technol.*, vol. 39, pp. 374–382, Nov. 1990.

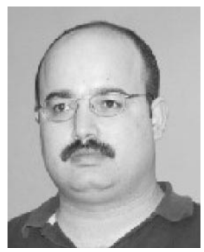
[6] S. P. Stapleton and F. C. Costescu, "An adaptive predistorter for power amplifier based on adjacent channel emissions," *IEEE Trans. Veh. Technol.*, vol. 41, pp. 49–56, Feb. 1992.

[7] E. G. Jeckeln, F. Beauregard, M. A. Sawan, and F. M. Ghannouchi, "Adaptive baseband/RF predistorter for power amplifiers through instantaneous AM-AM and AM-PM characterization using digital receivers," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, Boston, MA, June 2000, pp. 489–492.

[8] Y. Yang, J. Yi, J. Nam, B. Kim, and M. Park, "Measurement of two-transfer characteristics of high-power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 568–571, Mar. 2001.

[9] J. H. K. Vuolevi, T. Rahkonen, and J. P. A. Mannien, "Measurement technique for characterizing memory effects in RF power amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 1383–1389, Aug. 2001.

[10] J. S. Kenney, W. Woo, L. Ding, R. Raich, H. Ku, and G. T. Zhou, "The impact of memory effects on predistortion linearization of RF power amplifiers," in *Proc. ISMOT Int. Microwave Opt. Technol. Symp.*, Montreal, QC, Canada, June 19–23, 2001, pp. 339–343.



Slim Boumaiza (S'00) received the B.Eng. degree in electrical engineering from the École Nationale des Ingénieurs de Tunis, Tunis, Tunisia, in 1997, the M.Sc.A. degree from the École Polytechnique de Montréal, Montréal, QC, Canada, in 1999, and is currently working toward the Ph.D. degree at the École Polytechnique de Montréal.

His current research interests are design, linearization, characterization and modeling of high-power and spectrum-efficient RF amplifiers.

Fadhel M. Ghannouchi (S'84–M'88–SM'93) received the B.Eng. degree in engineering physics and the M.S. and Ph.D. degrees in electrical engineering from the École Polytechnique de Montréal, Montréal, QC, Canada, in 1983, 1984, and 1987, respectively.

He is currently a Professor with the Département de Génie Électrique, École Polytechnique de Montréal, where, since 1984, he has taught electromagnetic and microwave theory and techniques. He has provided consulting services to a number of microwave companies. He is also the founder of AmpliX Inc., Montréal, QC, Canada, a company that offer linearization products and services to wireless and satcom equipment manufacturers. His research interests are in the areas of microwave/millimeter-wave instrumentation and measurements, nonlinear modeling of microwave active devices, and design of power and spectrum-efficient microwave amplification systems.

Dr. Ghannouchi is a Registered Professional Engineer in the Province of Quebec, Canada. He has served on the Technical Committees of several international conferences and symposiums.